

Annual Technical Summary

Development of Semi-Empirical Attenuation Relationships for the CEUS

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Investigations Undertaken

The objective of this project was to develop an alternative semi-empirical ground motion attenuation relationship for the central and eastern United States (CEUS) using the hybrid empirical method. This attenuation relationship can be used in the regional assessment of seismic hazards including that conducted by the National Seismic Hazard Mapping Program. The method for accomplishing this objective involves modifying existing empirical attenuation relationships in the western United States (WUS) using adjustment factors calculated from the ratio of theoretical ground motions between the CEUS and WUS which are based on the stochastic simulation method.

Results

The mathematical framework of the hybrid empirical method is too involved to present in this report. Its full development will be included in the Final Technical Report. Instead, I will describe the six steps that are required to implement the method and how these steps were applied to the development of a semi-empirical attenuation relationship and a relationship for the aleatory standard deviation of ground motion for the CEUS. In the Final Technical Report each of these steps will be described mathematically.

Basic Framework and Methodology

The six steps that are required to apply the hybrid empirical method to the development of a semi-empirical attenuation relationship for the CEUS are as follows:

1. Select the host and target regions, in this case the WUS and CEUS, respectively.
2. Select a suite of empirical attenuation relationships from the host region (WUS) that can be used to calculate the strong-motion parameters and their variability for a selected set of magnitudes, distances, and other seismological parameters for which ground-motion estimates in the target region (CEUS) are desired.
3. Select seismological models for the host (WUS) and target (CEUS) regions and calculate theoretical ground-motion estimates and their variability for the same set of strong-motion parameters, magnitudes, distances, and seismological parameters defined in Step 2.
4. Calculate adjustment factors and their variability by dividing the theoretical ground-motion estimates from the target region (CEUS) by those from the host region (WUS).
5. Calculate hybrid empirical ground-motion estimates for the target region (CEUS) by multiplying the empirical ground-motion estimates from the host region (WUS) by the theoretical adjustment factors between the target and host regions.
6. Using regression analysis, develop a semi-empirical attenuation relationship for the median ground motion as well as relationships for the random variability of ground motion and the uncertainty in both the median ground motion and the mean random variability of ground motion for the target region (CEUS) from the hybrid empirical ground-motion estimates.

A brief description of the application of each of these steps to the develop of a semi-empirical attenuation relationship for the CEUS is given below.

Selection of Host and Target Regions (Step 1)

For this study, the target region, the CEUS, is defined as the region of eastern North America described by Toro *et al.* (1997) as the Midcontinent. It includes the area bounded on the west by the Rocky Mountains and on the south by the Gulf Coastal Plain. The CEUS is a good candidate for the application of the hybrid empirical method because it has been well studied seismologically. For the host region, I selected the WUS because of the large number of reliable empirical attenuation relationships that are available for this region and because it also has been well studied seismologically. It consists of the shallow crustal region of North America west of the Sierra Nevada and Cascade Mountains. Most of the strong-motion recordings in this region come from California, although many of the empirical attenuation relationships from this region include selected worldwide recordings from tectonic environments similar to the WUS.

Empirical Estimates of Ground Motion for WUS (Step 2)

I selected the empirical attenuation relationships of Abrahamson and Silva (1997), Campbell (1997), Sadigh *et al.* (1997), and Campbell and Bozorgnia (2000) to derive the empirical

estimates for the WUS. All of these investigators are recognized experts in empirical strong-motion modeling and collectively represent a wide range of differing opinions regarding the mathematical forms, databases, and regression techniques commonly used to develop empirical attenuation relationships. The attenuation relationship of Boore *et al.* (1997) was not used because it was found to give unrealistic hybrid empirical ground-motion estimates when theoretical adjustment factors were applied due to its functional form. It would also have been necessary to compute ground motions for a large number of different fault geometries in order to relate the distance measure used in this relationship to those used in the other relationships. The distance measures from the other attenuation relationships were similar enough that it was not necessary to account for differences in fault geometry. I used two attenuation relationships developed by Campbell, which at first might appear to be redundant. However, these relationships use different functional forms and seismological parameters and give significantly different estimates of ground motion. Both were used because the newer relationship cannot yet be considered a replacement of the former since it has not yet undergone sufficient peer review.

The selected attenuation relationships were used to calculate the average horizontal component (i.e., the geometric mean) of peak ground acceleration (PGA) and 5%-damped pseudoabsolute response spectral acceleration (PSA) for natural periods ranging from 0.02 to 4.0 sec. PGA was assumed to represent the value of PSA at 0.01 sec. For those attenuation relationships that did not provide spectral ordinates at the higher frequencies, I estimated them by interpolation using interpolation factors derived from the relationships that did. Such high frequencies were necessary to accommodate the high predominant frequencies of PSA on very hard rock in the CEUS. Only two seismological parameters were included as variables in deriving the empirical estimates: magnitude and distance. I considered the variability in ground motion from all other seismological parameters to be aleatory (random) variability since in most applications these parameters will not be known and their affect on ground motion is not necessarily the same in the CEUS as it is in the WUS. Estimates were made for magnitudes ranging from 5.0 to 8.2 in increments of 0.2 and for distances of 1, 2, 3, 5, 7, 10, 20, 30, 40, 50, 70, 100, 130, 200, 300, 500, 700 and 1000 km.

All of the empirical attenuation relationships use moment magnitude M_w to characterize earthquake size so no adjustment for magnitude scales was necessary. The distance measure r_{rup} was used to characterize distance in this study. The distance measure r_{seis} used by Campbell (1997) and Campbell and Bozorgnia (2000) was easily related to r_{rup} by setting it to 3 km for $r_{rup} < 3$ km. Abrahamson and Shedlock (1997) discuss the differences among these two distance measures.

All of the relationships were evaluated for local site conditions typically described as WUS generic rock. According to Boore and Joyner (1997), a generic rock profile has an average shear-wave velocity in the top 30m of around 620 m/s. The definition of WUS generic rock depends on the particular attenuation relationship. For the Abrahamson and Silva (1997) and Sadigh *et al.* (1997) attenuation relationships, their so-called rock categories were assumed to be generic rock. Generic rock for the Campbell (1997) relationship was defined by setting $S_{SR} = 1$,

$S_{HR} = 0$, and $D = 1$ km as recommended in Campbell (2000). Generic rock for the Campbell and Bozorgnia (2000) relationship was defined by setting $S_{SR} = 0.5$, $S_{HR} = 0.5$, and $S_{PS} = 0$.

All of the relationships were evaluated for a random faulting mechanism since it is not known whether the faulting factors used in the empirical attenuation relationships are appropriate for the CEUS. A random faulting mechanism for the Campbell and Bozorgnia (2000) relationship was defined by setting $F_{RV} = 0.25$ and $F_{TH} = 0.25$. For all of the other attenuation relationships a random faulting mechanism was defined by setting $F = 0.5$.

The aleatory standard deviation was increased for those attenuation relationships that were evaluated for random values of some seismological parameters. Adjustments were made for the sediment depth term D in the Campbell (1997) relationship and for the faulting mechanism terms in all of the attenuation relationships. No adjustment was made for the hanging-wall term HW in the Abrahamson and Silva (1997) relationship since this term affects such a small number of recordings that it does not have a measurable impact on the aleatory variability. This term was set to zero (no hanging-wall effects) for this study.

Theoretical Ground Motion Estimates for WUS and CEUS (Step 3)

Based on its success in modeling a wide range of ground motions (Boore, 2002), I selected the stochastic simulation method in conjunction with a one-corner-frequency, omega-square source spectrum to estimate the median theoretical ground motions and their epistemic variability (scientific uncertainty) for the host and target regions. I used the computer program SMSIM developed by Boore (1996) to perform the calculations. Simulations were performed for the same magnitudes and distances that were used to evaluate the empirical attenuation relationships.

The key to the calculation of theoretical ground motion is the selection of an appropriate set of seismological parameters to use with the stochastic method. For this study representative seismological parameters for the WUS (principally California), with the exception of the stress drop $\Delta\sigma$ and the attenuation within the upper kilometer or so beneath the site κ_0 , were taken from Atkinson and Silva (2000). This model uses the geometric and path attenuation terms of Raoof *et al.* (1999) and the WUS generic rock crustal velocity and amplification model of Boore and Joyner (1997). I chose to use $\Delta\sigma = 100$ bars and $\kappa_0 = 0.04$ sec based on Boore and Joyner's (1997) comparison of stochastically generated and empirically generated response spectra. These values produce hybrid empirical estimates of response spectra at small magnitudes and moderate distances that compare favorably with the theoretical estimates for the CEUS, giving some credibility to these values.

Representative seismological parameters for the CEUS were taken from Atkinson and Boore (1998) based primarily on the source parameterization of Frankel *et al.* (1996). This model uses the geometric attenuation, path attenuation, source duration, and path duration terms of Atkinson and Boore (1995) and the CEUS hard-rock crustal velocity and amplification model of Boore and Joyner (1997).

I assumed that the epistemic variability in the theoretical ground-motion estimates for the WUS were negligible since the seismological parameters derived for this region are well constrained by strong-motion recordings. However, many of the seismological parameters in the CEUS were estimated from limited data, generally only at small magnitudes and large distances, or from theoretical models. As a result there is considerable epistemic variability associated with the theoretical ground-motion estimates in this region. Following the approach used in the Trial Implementation Project (Savy *et al.*, 1999) in the CEUS, I included epistemic variability in the median value of the stress drop $\Delta\sigma$, the median value of the path attenuation term Q , and the median value of the site attenuation term κ_0 . I used the alternative values for these parameters recommended by EPRI (1993) and Toro *et al.* (1997) with a slightly different weighting scheme. I considered the uncertainty in all of the other seismological parameters to be aleatory and, therefore, included as part of the WUS aleatory standard deviation derived from the empirical ground-motion estimates. This is a departure from EPRI (1993) and Toro *et al.* (1997) who assumed that only the uncertainty in the median value of the stress drop was epistemic. This brings up the difficulty in trying to separate variability into its aleatory and epistemic components. My definition of aleatory variability is based on what was considered to be the state of the art at the time of the Yucca Mountain PSHA Project (Stepp *et al.*, 2001) and the Trial Implementation Project (Savy *et al.*, 1999). This concept could change in the future as research in this area progresses.

Theoretical Adjustment Factors between CEUS and WUS (Step 4)

I used the theoretical ground-motion estimates calculated in Step 3 to calculate the median theoretical adjustment factors and their epistemic standard deviations for the CEUS by dividing the CEUS estimates by the WUS estimates. For this study I decided not to develop equations for the adjustment factors and their epistemic standard deviations after reviewing the results. These equations would have required a complicated functional relationship between magnitude and distance—one that would not have been easily parameterized. On the other hand the hybrid empirical estimates were found to be well behaved and easily modeled.

Hybrid Empirical Ground-Motion Estimates for CEUS (Step 5)

I calculated the median hybrid empirical ground-motion estimates for the CEUS by multiplying the median empirical ground-motion estimates for the WUS by the median theoretical adjustment factors for each of the magnitudes, distances, and ground-motion parameters defined in Step 2. I assumed that the distances used in the theoretical calculations were equivalent to the distance measure r_{rup} used for the empirical estimates. I used as the hybrid empirical estimate of the aleatory standard deviation of ground motion the mean adjusted aleatory standard deviation from the empirical ground-motion estimates. The empirical estimates are only valid to a distance of 70–100 km because of the lack of recordings at greater distances. The hybrid empirical estimates were extended to 1000 km using the theoretical estimates after adjusting them to match the empirical estimates at 70 km.

Hybrid Empirical Attenuation Relationship for CEUS (Step 6)

I used the hybrid empirical ground-motion estimates to develop a semi-empirical attenuation relationship for the CEUS using regression analysis. The functional form of the relationship was developed from trial and error using functional forms proposed in previous empirical studies. A similar relationship was developed for the aleatory standard deviation. The resulting attenuation relationship is given by the expression

$$\ln Y = c_1 + c_2 M_w + c_3 (8.5 - M_w)^2 + c_4 \ln[f_1(M_w, r_{rup})] + f_2(r_{rup}) + (c_9 + c_{10} M_w) r_{rup} \quad (1)$$

where

$$f_1(M_w, r_{rup}) = \sqrt{r_{rup}^2 + [c_5 \exp(c_6 M_w)]^2} \quad (2)$$

$$f_2(r_{rup}) = \begin{cases} c_7 (\ln r_{rup} - \ln r_1) & \text{for } r_{rup} > r_1 \\ c_8 (\ln r_{rup} - \ln r_2) & \text{for } r_{rup} > r_2 \end{cases} \quad (3)$$

and Y is the geometric mean of the two horizontal components of PGA or PSA in g , M_w is moment magnitude, r_{rup} is the closest distance to fault rupture in km, $r_1 = 70$ km, and $r_2 = 130$ km.

The relationship for the aleatory standard deviation of ground motion is given by the expression

$$\sigma_{\ln Y} = \begin{cases} c_{11} + c_{12} M_w & \text{for } M_w < M_1 \\ c_{13} & \text{for } M_w \geq M_1 \end{cases} \quad (4)$$

where $M_1 = 7.16$.

The regression coefficients c_1 through c_{13} are given in Table 1. Figures 1a–1d show the magnitude and distance dependence of PGA and PSA at periods of 0.2, 1.0, and 3.0 sec predicted by Equation (1) compared with the hybrid empirical ground-motion estimates that were used to develop it. Figures 1e–1f show a similar comparison of the 5%-damped pseudoacceleration response spectra. The error involved in fitting Equation (1) to the hybrid empirical estimates is very small and does not contribute measurably to the aleatory standard deviation.

Non-Technical Summary

The objective of this project was to develop an alternative semi-empirical ground motion attenuation relationship for the central and eastern United States (CEUS) using the hybrid empirical method. This attenuation relationship can be used in the regional assessment of

seismic hazards, including that conducted by the National Seismic Hazard Mapping Program. The attenuation relationship will improve the ability to predict ground motion in the CEUS where strong-motion data are limited. The method for accomplishing the project objective involves modifying existing empirical attenuation relationships in the western United States (WUS) using adjustment factors based on the ratio of theoretical ground motions between the CEUS and WUS calculated using the stochastic simulation method. The following tasks related to the project objective were completed during the reporting period: (1) the mathematical framework of the method was developed, (2) the WUS empirical attenuation relationships were selected and evaluated, (3) the seismological parameters used with the stochastic simulation method were developed, (4) the theoretical ground motions were calculated, (5) a semi-empirical attenuation relationship was developed, and (6) a relationship for the aleatory standard deviation of ground motion was developed. Yet to be developed are epistemic standard deviations for the median ground motion and the mean aleatory standard deviation.

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Table 1 – Regression Coefficients

<i>T</i> (s)	<i>c</i> ₁	<i>c</i> ₂	<i>c</i> ₃	<i>c</i> ₄	<i>c</i> ₅	<i>c</i> ₆	<i>c</i> ₇	<i>c</i> ₈	<i>c</i> ₉	<i>c</i> ₁₀	<i>c</i> ₁₁	<i>c</i> ₁₂	<i>c</i> ₁₃
0.01	0.0305	0.633	-0.0427	-1.591	0.683	0.416	1.140	-0.873	-0.00428	0.000483	1.030	-0.0860	0.414
0.02	1.3535	0.630	-0.0404	-1.787	1.020	0.363	0.851	-0.715	-0.00388	0.000497	1.030	-0.0860	0.414
0.03	1.1860	0.622	-0.0362	-1.691	0.922	0.376	0.759	-0.922	-0.00367	0.000501	1.030	-0.0860	0.414
0.05	0.3736	0.616	-0.0353	-1.469	0.630	0.423	0.771	-1.239	-0.00378	0.000500	1.042	-0.0838	0.443
0.075	-0.0395	0.615	-0.0353	-1.383	0.491	0.463	0.955	-1.349	-0.00421	0.000486	1.052	-0.0838	0.453
0.10	-0.1475	0.613	-0.0353	-1.369	0.484	0.467	1.096	-1.284	-0.00454	0.000460	1.059	-0.0838	0.460
0.15	-0.1901	0.616	-0.0478	-1.368	0.461	0.478	1.239	-1.079	-0.00473	0.000393	1.068	-0.0838	0.469
0.20	-0.4328	0.617	-0.0586	-1.320	0.399	0.493	1.250	-0.928	-0.00460	0.000337	1.077	-0.0838	0.478
0.30	-0.6906	0.609	-0.0786	-1.280	0.349	0.502	1.241	-0.753	-0.00414	0.000263	1.081	-0.0838	0.482
0.50	-0.5907	0.534	-0.1379	-1.216	0.318	0.503	1.166	-0.606	-0.00341	0.000194	1.098	-0.0824	0.508
0.75	-0.5429	0.480	-0.1806	-1.184	0.304	0.504	1.110	-0.526	-0.00288	0.000160	1.105	-0.0806	0.528
1.0	-0.6104	0.451	-0.2090	-1.158	0.299	0.503	1.067	-0.482	-0.00255	0.000141	1.110	-0.0793	0.543
1.5	-0.9666	0.441	-0.2405	-1.135	0.304	0.500	1.029	-0.438	-0.00213	0.000119	1.099	-0.0771	0.547
2.0	-1.4306	0.459	-0.2552	-1.124	0.310	0.499	1.015	-0.417	-0.00187	0.000103	1.093	-0.0758	0.551
3.0	-2.2331	0.492	-0.2646	-1.121	0.310	0.499	1.014	-0.393	-0.00154	0.000084	1.090	-0.0737	0.562
4.0	-2.7975	0.507	-0.2738	-1.119	0.294	0.506	1.018	-0.386	-0.00135	0.000074	1.092	-0.0722	0.575

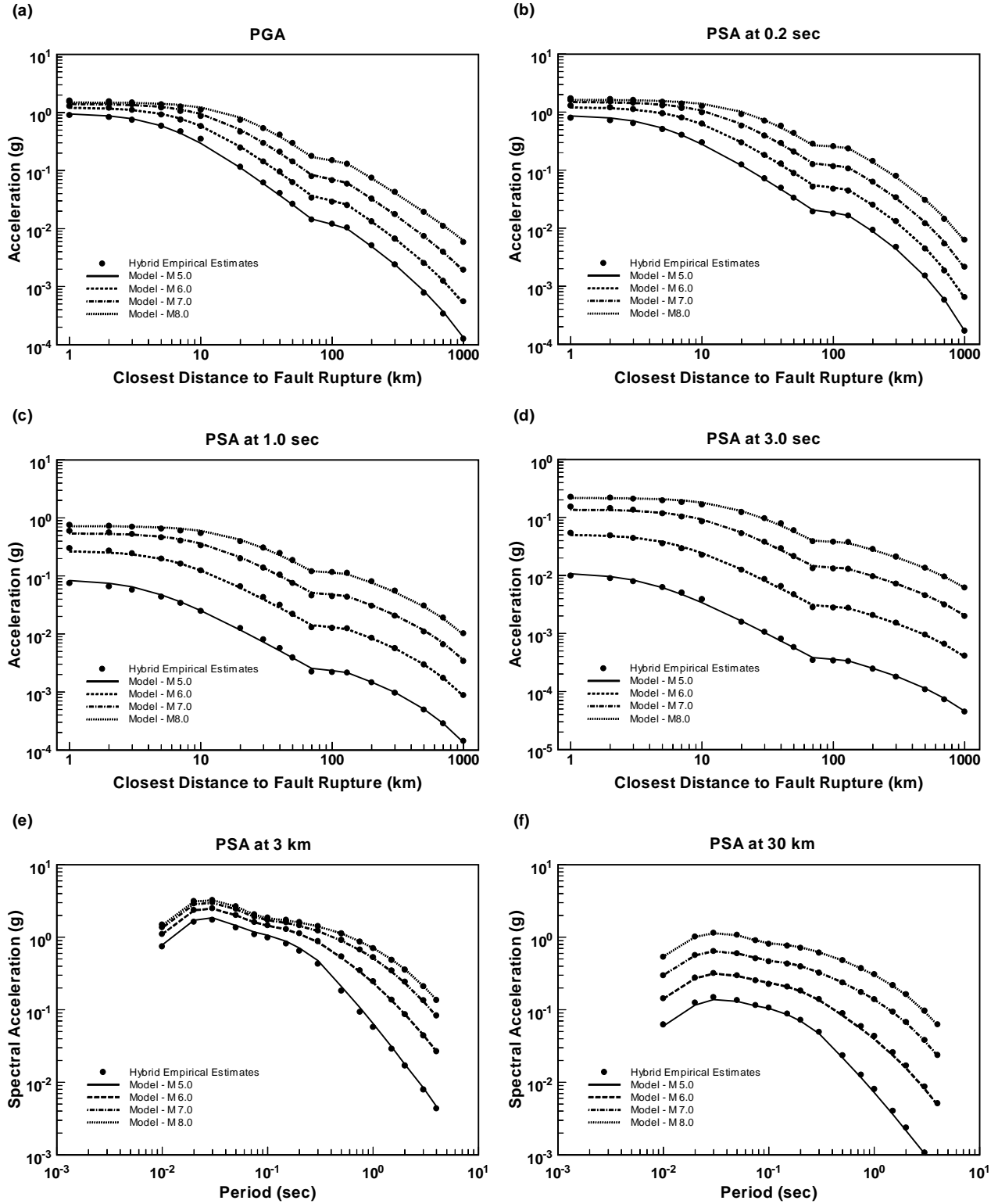


Figure 1. – Comparison of hybrid empirical ground-motion estimates with predictions from the regression model: attenuation with distance for (a) PGA, (b) PSA at 0.2 sec, (c) PSA at 1.0 sec, and (d) PSA at 3.0 sec; 5%-damped PSA response spectra at distances of (e) 3 km and (f) 30 km.